NON-LINEAR UNSTEADY WAVE LOADS ON LARGE HIGH-SPEED WAVE PIERCING CATAMARANS.

BY

WALID AMIN

BSc (Hons) (1995), MSc Naval Architecture and Marine Engineering, Alexandria University (2000)

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To whom we owe most

To whom we love most

To whom we respect most

To Raham

To Karma, Nourin and Taha

To my parents

DECLARATION OF ORIGINALITY

This Thesis contains no material that has been accepted for a degree or diploma by the University of Tasmania or any other institution, and to the best of my knowledge and belief no material previously published or written by another person except where due acknowledgement is made in the text of the thesis

Walid Amin May 2009.

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ABSTRACT

The current work investigates the slamming characteristics of wave piercing catamarans through the analysis of sea trials data of the 98 m Incat sea frame “Hull 061”, built in Tasmania, Australia and currently serving in the US Navy combat fleet. The importance of this sea trials data is that the ship was tested in severe sea conditions to assess her suitability for military operations and to define her operational envelope. New signal processing techniques such as Wavelet Transforms are used in analysing slamming data for two main purposes, slamming identification and modal analysis in time and frequency domains simultaneously. The Wavelet Transforms were found superior to conventional signal processing tools such as Fast Fourier Transform and Short Time Fourier Transform.

The structural strength of wave piercing catamarans is studied by introducing a novel sea trials analysis for structural performance assessment in an attempt to simulate real loading conditions. The methodology was tested on normal linear wave loading (without slamming) and was found satisfactory. A “Reverse Engineering” approach is introduced to predict slamming loads during sea trials by using the capabilities of Finite Element Analysis using the well known software PATRAN/NASTRAN[1]. To increase the efficiency of this approach, the load parameters, spatial location and distribution, were investigated through model tests of a similar but larger 112 m Incat hydro-elastic model in the Australian Maritime College towing tank facility. Based on pressure measurements, proper slam load models can be more accurately and efficiently introduced in the finite element analysis.

Quasi-static analysis was first performed to examine its suitability to analyse such fast time varying loads. Difficulties in comparison procedures between numerical simulations and trials data have strongly highlighted the need for dynamic analysis. Direct transient dynamic analysis was performed using the dynamic solver of the same software package. Good agreement with trials data was found. The suggested procedure and slamming loading patterns used in the numerical simulation is then verified and can be regarded as a solid base for verification of other theoretical design models.

[1] MSC Software Corporation, USA

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CONTENTS

1 INTRODUCTION

1.1 Background

Increased demand in high-speed sea transportation has led to rapid and ongoing development of high-speed marine vehicles especially multi-hull ships. However, the development of multi-hull ships goes back thousands of years ago when it was first presented by the Polynesian seafarers in the form of "proa", Figure 1.1 and the "pre-columbian" raft built by the ancient South Americans, International Polynesian Portal [1]. The 17th century witnessed the first modern building of catamarans when the first conceptual catamaran "double-bottom" was built by Sir William Petty in 1660, Pumfrey [2].

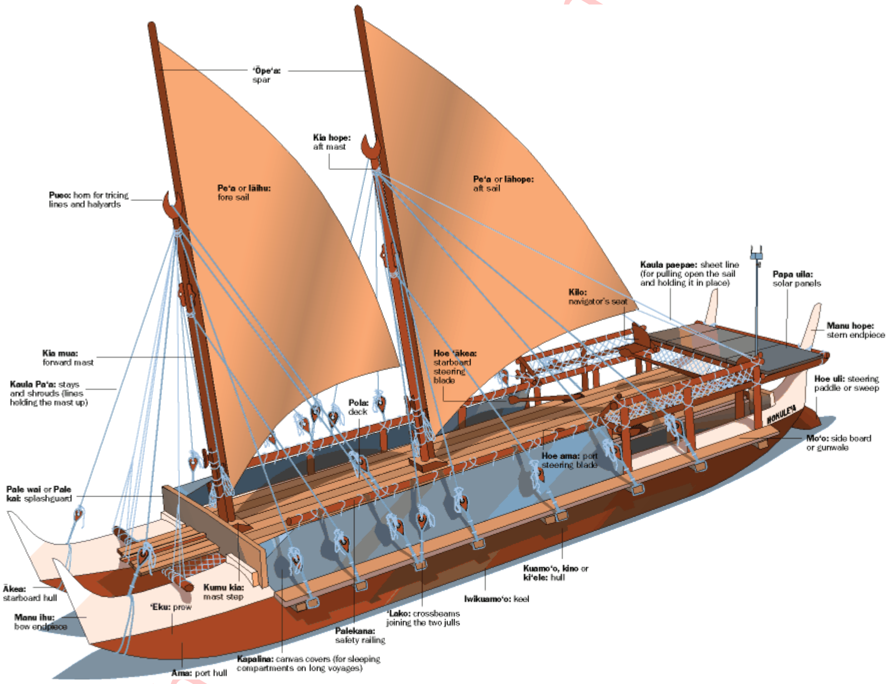

Figure 1.1: Artistic presentation of "Proa" boats built by the Polynesians, International Polynesian Portal [1].

Steam paddle wheel powered catamarans operating as ferry boats and river craft appeared in the UK and US in early 1800's, Clark et al. [3].Since 1980's to early 1990's, the number of built catamarans increased rapidly operating as passenger ferries in the range of 25 to 40 m with passenger capacities up to 400 passengers. A typical catamaran during this period is shown in Figure 1.2.

Figure 1.2: Typical 30 m fast passenger catamaran during 1980's built by Incat Tasmania.

Figure 1.3: First car/passenger wave piercing catamaran built by Incat Tasmania, 1993.

Figure 1.4: The 125 m HSS 1500 Stena built by Finnyard, 1996.

At this stage, market demands highlighted the need for car/passenger ferries which finally led to the introduction of new designs which are capable of carrying cars and light weight cargo. The first boat to be built to meet these requirements was the Condor 10, LOA 74 m and built by Incat Tasmania in 1993. In 1996, Finnyard in Finalnd launced the HSS (high speed ship) “Stena Line”, a 125 m car/passenger ferry that was capable of carrying 1520 passenger, 375 cars and operating at speed of 40 knots, Figure 1.4.

Figure 1.5: The 96 m HMAS Jervis Bay (HSV-X1) wave piercing catamaran built by Incat Tasmania, 1998.

Figure 1.6: The 98m HSV 2 Swift wave piercing catamaran built by Incat Tasmania, 2003.

The advantages of high speed vessels, with a relatively high payload, drew attention to the applicability of high-speed catamarans in military operations as logistics, transport and rescue support ships. In 1999, Incat Tasmania chartered the first military 86 m boat to the Royal Australian Navy to serve as a fast sea link for Australian troops between Darwin and Dili in East Timor, during the operation of the Australian-led INTERFET peacekeeping taskforce. The ship was capable of sailing 430 nautical miles (800 km) in approximately 11 hours, at an average speed of approximately 45 knots (83 km/h), far faster than vessels of comparable size and role in the region. During the two years of the ship's charter by the Royal Australian Navy, HMAS Jervis Bay made 107 trips between Darwin and East Timor, shipping 20,000 passengers, 430 vehicles and 5,600 tonnes of freight, becoming known as the "Dili Express".

Figure 1.7: The 80 m X-Craft catamaran, designed by Nigel Gee and Associates Ltd, and built by Nichols Bros. boat builders, Washington, USA.

In 1998, the US Navy chartered its first 96 m wave piercing catamaran known as HSV X1, Figure 1.5, to test the new technologies and concepts associated with the Chief of Naval Operations's "Seapower 21" plan. The vessel has the ability to ferry up to 325 combat personnel and 400 tons of cargo up to 3000 miles one way at speeds in excess of 40 knots. Ordered for the US Navy in 2002, the 98 m Spearhead TSV 1X benefited from performance and engineering data gathered through the operation of HSV X1. HSV 2 Swift (the vessel under consideration through this thesis), was completed to the US Navy specification and delivered in 2003. The vessel underwent an extensive sea trials program to assess her operational envelope for military applications. In 2005, the US navy tested a semi-swath catamaran (without the centre bow configuration) through the X-Craft, an experimental platform for an innovative new class of fast, littoral, warfare craft, designed by BMT Nigel Gee and Associates Ltd. The vessel is the largest catamaran ever to be built in the US and one of the fastest large naval craft in the world and is capable of operation at speeds in excess of 50 knots (in calm seas), Figure 1.7.

Figure 1.8: First wave piercing catamaran, "Tassie Devil 2001", built by Incat Tasmania in 1986.

Figure 1.9: The 107 m Hawaii Superferry built by Austal Ships (Western Australia), 2007.

When the use of catamarans extended from sheltered waters to more exposed sea going operation, motion problems in rough seas started to arise. Excessive pitching in following seas caused severe impacts on the bridging structure that connects the demi-hulls. The centre bow conceptual design was first introduced by Philip Hercus (Incat Designs Sydney) to reduce the pitching motion in head and following seas and in particular to avoid deck diving when the bow enters the water in following seas. The first wave piercing catamaran with a centre bow configuration was built by Incat Tasmania in 1986, Figure 1.8. From that time and on, almost all Incat ships were fitted with centre bows. In contrast, Austal Ships, the main competitor of Incat in the international market, kept the conventional catamaran configuration (with flat wet deck). Austal designs of sea going catamarans have a different strategy to avoid bow diving by introducing a "sufficient" air gap (or tunnel height) so that the wet deck remains relatively clear from the water surface in the designated operation conditions. Similar vessels of comparable capacities and lengths to Incat designs have been built such as the 107 m Hawaii Superferries, Figure 1.9.

1.2 Structural configuration of Incat wave piercing catamarans

In order to familiarise the reader with the novel design of these vessels and the notations used through the thesis, the general structural configuration is presented in this section.

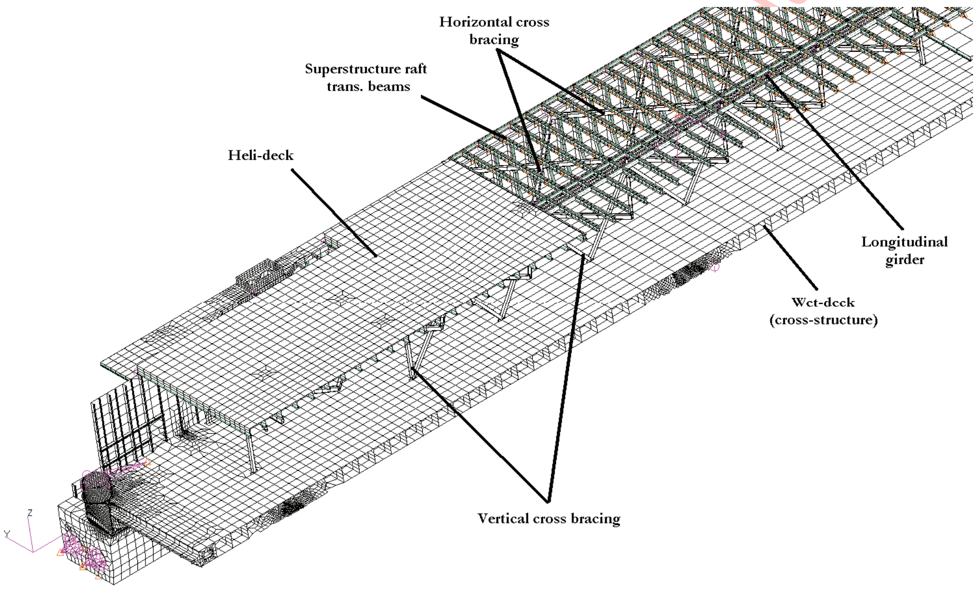

Figure 1.10: Cut away port side section of Incat hull girder showing horizontal and vertical cross bracing.

One of the major characteristics of these vessels is the high service speed they can operate at. This high speed can be achieved when lighter structures can be built to the required strength to withstand the environmental loads. Therefore, the first design goal is usually to optimise the deadweight to lightship ratio whilst maintaining structural integrity and reliability. Thus, structural optimisation is an essential task during the preliminary design process. In addition to the normal longitudinal framing system onboard monohulls, cross bracing (in the vertical and horizontal directions) is used to provide structural strength to withstand longitudinal and lateral torsional deformations as shown in Figure 1.10.

The superstructure is supported by transverse beams (the superstructure raft, Figure 1.11) which are connected to the main hull girder through rubber mounts to reduce the vibration levels in the passenger lounges. Incat catamarans are characterised by a centre bow between the demi-hulls. The centre bow length ranges between 19 to 30% of the waterline length. Its main purpose is to counteract the bow diving in following seas as well as reducing the vessel pitching motion by offering extra buoyancy as the bow pitches into the wave. Consequently, the vessel has two archways between the centre bow and demi-hulls in the forward part of the vessel. Behind the centre bow, the wet-deck is flat, Figure 1.12

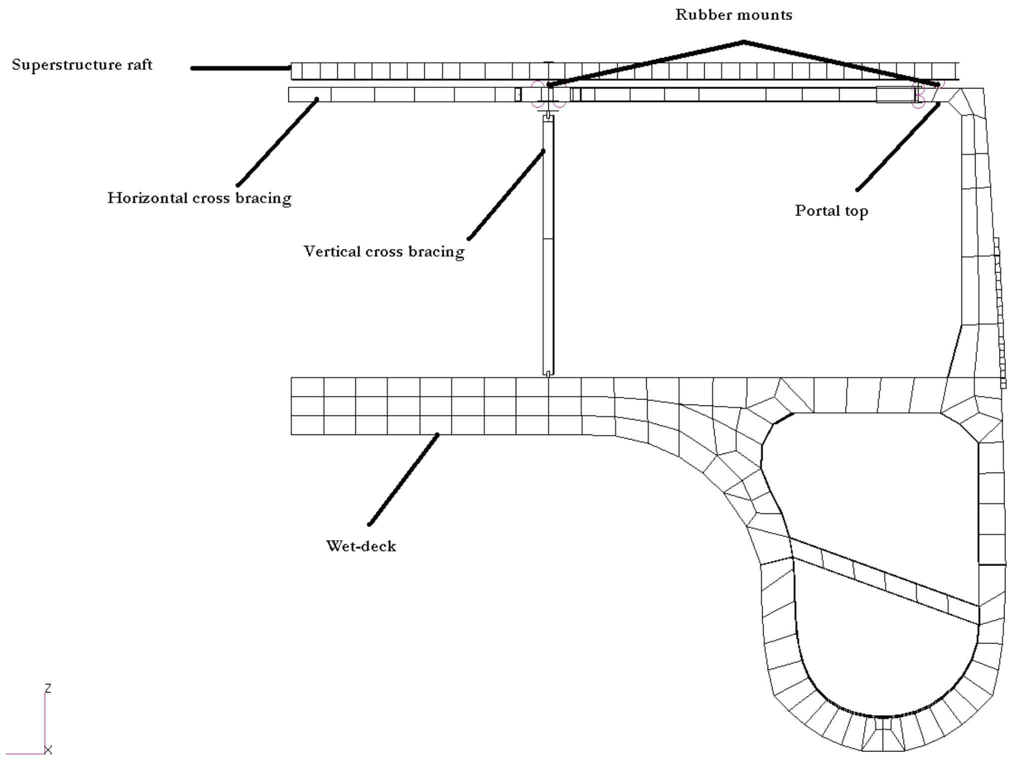

Figure 1.11: Cross section of Incat hull girder.

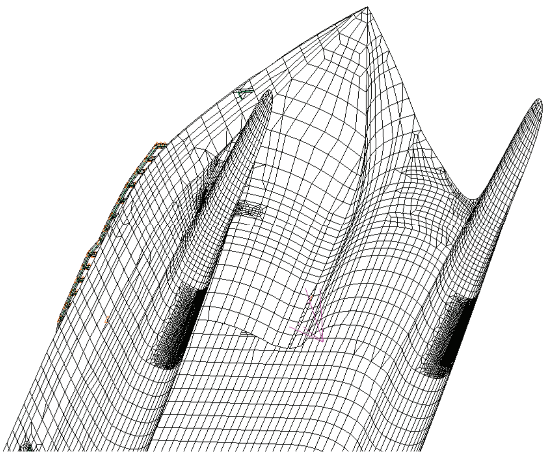

Figure 1.12: Characteristic centre bow of Incat catamarans.

1.3 Problem definition

When the vessel is operating in rough seas, the ship may experience water impact loads due to the excessive relative motion between the vessel and the waves. A shudder or vibration occurs following such impacts known as whipping. Severe slamming loads might result in abrupt changes in vessel motions and high stress levels which may in turn cause structural damage. Such damage has a direct influence on short term cost due to the cost of repair and loss of service time; in addition, long term losses might occur due to bad publicity of stiff ship motions.

Figure 1.13: Damage of bow structure on HSS 1500 Stena due to severe slamming loads.

Figure 1.14: Side shell buckling as a consequence of severe slamming loads, Hull 50 of Incat Tasmania.

Slamming on multihull ships is different from slamming on monohulls in terms of slam location and severity. Twin hull ships experience unique type of slamming called wet-deck slamming, when the underside of the cross deck structure comes in contact with the wave surface in the presence of sufficient relative motion between the vessel and the water surface. Serious damage occurred on the HSS 1500 Stena bow structure due to a severe slamming event in rough seas, Figure 1.13.

Deformation of longitudinal stiffeners has been reported on an 86 m Austal vessel due to severe slamming loads, Rothe et al. [4]. On wave piercing catamarans, Hull 050 of Incat suffered side shell buckling, Figure 1.14, and tripping of brackets in the centre bow area, Figure 1.15. In general, severe slamming load effects can result in:

(a) Localised dishing of plating between longitudinal stiffeners and side frames.

(b) Distortion of centre bow T-bar longitudinal stiffeners.

(c) Side shell buckling.

(d) Distortion of frames and stiffeners aft of the centre bow.

(e) Crack propagations due to the effect of whipping in the form of material fatigue.

Figure 1.15: Tripping of brackets and vertical stiffeners in the centre bow of Hull 50 of Incat Tasmania due to severe slamming load.

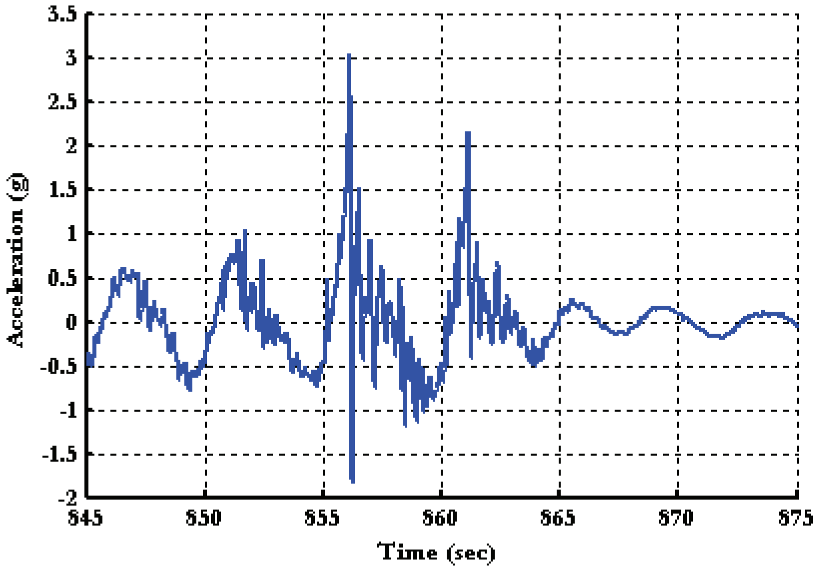

Figure 1.16: Severe vertical bow vertical acceleration during Hull 061 sea trials in head seas, sea state 5, 20 knots speed.

Incat Hull 061 (HSV 2 Swift) has shown greatly improved structural integrity, demonstrated when the vessel underwent extensive sea trials program by the US Navy to define its operational envelope. The vessel was tested significantly beyond the service criterion she was designed to withstand according to the DNV rules. Consequently high motion acceleration records were reported, Figure 1.16. As will be shown in this thesis, the calculated loads during the design process were smaller than those imparted on the structure during trials. However, the ship withstood these high loads without any structural damage. This means that the ship structure may be further optimised to reduce the lightship displacement and consequently increase the payload.

However, the calculation of slam loads on large catamarans fitted with a centre bow is a complex task and extreme loads to date have not been established through a proven theoretical approach. Unfortunately the kinematics of slamming events is also not well understood on large high-speed catamarans. Classification of slamming events and the factors affecting the slamming occurrences can only be evaluated by full scale measurement and/or model testing. In comparison to the extensive work that has been done for slamming on monohulls, such as that due to Aertssen [5]and Iaccarino et al. [6], little work has been published on full scale measurement of loads and motions of large high speed catamarans. Roberts et al. [7] extrapolated sea trials stresses of two 81 m and 86 m Incat catamarans at a probability of 10^{-8} using Weibull and Gumbel extreme value plots. The analysis assumes that extrapolated full scale stresses can be directly compared with the FE model stresses at the same locations in a quasi-static analysis. Steinmann et al. [8]

extrapolated sea trials extreme value stresses at a probability of 10^{-8} using the Ochi extrapolation procedure which assumes a linear relationship between stresses and wave height which is not true for moderate to heavy seas for large high speed catamarans. Individual slamming events were identified during data post processing. The peak slam responses were compared to the quasi-static global response levels as defined by classification societies. The used extreme value analysis, in both cases, was implemented to compensate for the dynamics of slamming. Thomas et al. [9] and Thomas et al. [10] have explored the slam dynamics extensively without extrapolation techniques to investigate the load values during an extreme slamming event that caused buckling of the superstructure shell plates on an 96 m Incat catamaran during her regular service across Cook Strait in New Zealand. The investigation resulted in improved understanding of slamming dynamics showing that the slamming load during this particular event is in excess of 1000 tonnes. In the current analysis, the author extended the investigation of slamming dynamics through the improvement of slamming identification techniques, quasi-static and dynamic finite element analysis (FEA) as well as conducting experimental measurements of dynamic pressures in regular waves on the centre bow and the bridging structure. The key novel objectives in the current work are:

(a) Introduction of new trials interpretation technique instead of the conventional calibration factors technique.

(b) The introduction of wavelet transform as a new signal analysis to investigate the ship structural performance during sea trials.

(c) Hydrodynamic pressure measurements on the centre bow and wet deck structure in regular waves.

(d) Introduction of the "reverse engineering" technique in prediction of the linear and non-linear wave loads using the capabilities of finite element analysis and sea trials data.

1.4 Scope of work

Sea trials analysis is an important approach for assessing new designs and has a direct impact on the evaluation of design methods and numerical models in respect to resistance, seakeeping, structural optimisation and loading models. Sea trials enable the designer to assess the design loading models and formulae used in the original design. Moreover, they help to understand the environmental loads that a ship would sustain in all working conditions and how the structure responds to these loads. The sea trials considered in this thesis are for Hull 61, an INCAT seaframe (HSV 2 Swift), originally a fast passenger/ferry design, re-configured for US Navy military purposes. The ship has undertaken extensive sea trials to investigate this hull configuration for military purposes and to determine her operational envelope.

A primary motivation behind the current work was the large motion responses observed during trials in high sea states, which exceeded the design values. Excessive accelerations are due to slamming impact loads which are not fully understood for this type of vessel. The goal of this work is to effectively understand the water impact problem, and the consequential structural loads using the sea trials data combined with the capabilities of finite element analysis. The strategy for achieving the specified goal can be summarised as follows:

(a) Identification of a signal analysis tool that is suitable for the analysis of non-stationary signals with transient events. This is required to derive a slamming identification technique.

(b) Analysis of slamming kinematics in terms of ship and water surface motion during the slamming events.

(c) Using finite element analysis capabilities, a quasi-static reverse engineering procedure was established in which a finite element model is loaded arbitrarily (but with input from the sea trials such as the wave condition, ship motions, etc.). The finite element strains were compared to the trials data for specific slam events. The load model was modified until a satisfactory agreement between trials strains and computed strains is achieved.

(d) A similar comparison approach was repeated using a full FE dynamic analysis.

The reverse engineering procedure is usually conducted when available theoretical models fail to predict comparable results with experiments or are inadequate for the problem under consideration. There are many methods to calculate the global loads on catamarans (see Holloway [11], Faltinsen et al. [12], Kring et al. [13], Kring et al. [14], Weems et al. [15], Ito et al. [16], Chan [17] and Chan [18]). However, fewer methods are available for slamming loads. Kvålsvold et al. [19] and Økland et al. [20] concluded that structural elasticity is necessary in the simulation and the predicted slamming loads are conservative when a two-dimensional approach is used. Haugen et al. [21] proposed a three dimensional approach and results were compared to sea trials of a 30 m catamaran satisfactorily.

However, the vessel relative velocity was predicted instead of being extracted from sea trials data. To date these methods have been verified against small size catamarans and without a centre bow configuration and therefore these methods are not suitable for analysis of the current vessel.

The current methodology of sea trials analysis such as Sikora et al. [22], is based on extraction of calibration factors for the strain gauges by applying a known load (known bending moment value for example) to the finite element model. The calibration factors are load independent and can be regarded as a local property of the position of the strain gauge. Thus, the calibration factors can be regarded as a transfer function between the applied load and local response. Consequently, if the structural response is known (from trials), then an equivalent loading (similar to the load used in determining the calibration factor but scaled up or down) can be obtained. The method works well for the underlying wave loads but is very conservative in regard to slam loads in which a wave is exaggerated unrealistically to simulate the high response of slamming. Nevertheless, the slam load is highly concentrated in the bow area and might result in local effects that will not be identified if the calibration factors procedure is used. Therefore, the current study employs a realistic interpretation of wave loads during actual trials conditions based on sea trials data, such as ship immersion and accelerations. The method forms a good reference foundation for validation of current and new analytical methods.

Normally, the first step in slamming analysis is the identification of slamming events. Slamming events are transient events (localised in time) and produce structural vibrations in the form of whipping at much higher frequency than the excitation wave frequency (localised in frequency). Traditional spectral analysis methods are not suitable for two reasons: firstly slamming is a transient process which contradicts the basic assumptions of conventional spectral analysis methods that assume stationary signals. Secondly, all time information is lost when transferring from the time domain to frequency domain. The wavelet transform is proposed as a tool to analyse slamming events as it can represent the signal in both time and frequency simultaneously.

Identification of the slam loading spatial distribution for finite element simulations is difficult due to the increased number of simulations. Therefore, it was proposed to conduct experimental pressure measurements in regular waves so that a clear view of the slam load spatial distribution could be obtained. Although the model testing is more costly than the running time of finite element simulation, the experimental work will increase the reliability of the predicted slam load distributions

1.5 General arrangement of the thesis

In chapter 2 of this thesis data from sea trials will be presented showing the characteristics of slam events using strain gauge, accelerometer and vessel motion records. A brief mathematical background of wavelet transform is presented emphasising the main advantages of wavelet transforms over conventional signal analysis methods. The wavelet transform is applied to test signals (similar to the impulse response of Single Degree Of Freedom, SDOF, system) to explore the slamming signature in the wavelet transform. The test is expanded to Multi Degree Of Freedom, MDOF, systems and finally was applied to real signals.

Pressure measurements on the centre bow and the wet deck structure are presented in Chapter 3. The main purpose of the experiments is to investigate the spatial distribution of slam loads by exploring the pressure distributions on the forward part of the vessel in the area of the centre bow and the wetdeck structure. The pressures were used to define the slam load location and spatial distribution (longitudinally and transversely). The resulting slam load distributions are used in the slam load model during FE simulations.

Quasi-static finite element analysis is presented in Chapter 4 for normal wave loadings without any slam to confirm the applicability of the proposed procedure. The FE modelling techniques are discussed in terms of the appropriate modelling methods (the element types used) for ship structures with special attention to the analysis of sea trials data (extraction of local strains at the strain gauge locations). Then, the analysis is extended to include severe slamming events. The quasi-static impulse is evaluated and the energy absorbed by the structure due to slamming loads is explored.

In chapter 5, the dynamic response of Incat catamarans with centre bow are investigated. Dry and wet (including fluid structure interaction) modal analysis is applied and the dominant natural frequencies are identified. Dynamic analysis of severe slamming events is presented employing the sea trials data (in terms of vessel motions, immersion and temporal load development, as well as overall system damping) and pressure measurements outcomes (in terms of load location, distribution). The load magnitude is changed systematically until a satisfactory match with trial strain values (peak response and subsequent whipping) is achieved.

No separate literature review chapter is included due to the diversity of the work in the thesis. Instead, it is included in each section's introduction and whenever it is necessary to reference previous work. Nomenclature is defined within the text when appropriate.